Strength of materials and masonry structures in Malawi

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ABSTRACT:

Strength properties of masonry materials commonly used for housing construction in formal and informal settlements in Malawi are investigated by means of laboratory testing, conducted on masonry prisms and panels. The tests are aimed at simulating actual field conditions and construction practices in the country. Based on observations from previous field surveys, specimens were prepared by local artisans using local commercially-produced bricks and various mortar types which were cured in uncontrolled conditions. The results reveal that the behaviour of the masonry in compression is governed by the low compressive strength of the bricks. It was also found that it is the quality of the brick-mortar bonding that governs the in-plane shear and out-of-plane flexural behaviour, which are critical for the resistance to horizontal loading, such as the earthquake action.

1 INTRODUCTION

As a developing country, Malawi faces tough economic conditions and continues to perform poorly on various macroeconomic indicators. Since poverty levels remain high, affordability and access to decent housing remain a major challenge for local communities. Unreinforced masonry is the prevailing construction type in both formal and informal settlements (Malawi Government, 2008; UN-Habitat, 2010).

Housing construction for low-income households is based on poor and low-cost materials, such as unburnt bricks or fired bricks bonded with mud mortar. The use of unburnt bricks is more common in rural areas. Higher income households generally use fired bricks bonded with cement mortar. Bricks are produced by local artisans with no quality assurance measures. Poor methods of production result in bricks of variable geometry and physical properties. The quality of mortar material is also variable, depending on the level of income. Apart from poor and variable construction materials and methods, lack of technical expertise and design codes contributes significantly to poor masonry construction (Novelli et al., 2018).

Malawi is prone to natural hazards such as earthquakes that affect integrity of the built environment. The country is located along the East African Rift System where large earthquakes of moment magnitude (M_w) 7+may occur (Hodge et al., 2015; Poggi et al., 2017).The impact of major disasters to local communities can be serious due to poor infrastructure. The 1989 Salima and the 2009 Karonga earthquakes severely affected tens of thousands of people, causing economic losses of US$28 million and US$14 respectively (Chapola & Gondwe 2016). Post-earthquake assessment of these past events showed that the damage was mainly caused by poor construction methods and materials. Structures with unburnt/burnt bricks and mud mortar suffered severe damage. In contrast, other more traditional building types, such as bamboo reinforced wattle structures, performed better than low-quality masonry structures (Ngoma & Mthinda, 2010).

The lessons learnt from previous disasters, in conjunction with the pressing needs related to rapid population growth and expansion of informal settlements, led to the recent release of the Safer House Construction Guidelines (Bureau TNM, 2016), as a joint effort of the Malawian Government and international aid organisation experts, to deal with the uncontrolled masonry construction in Malawi. These guidelines consist of simple structural qualitative instructions based on international experience and practice (IAEE, 2004), which can improve the performance of housing structures built with poor-quality materials. Meanwhile, there is a need for proper quantitative assessment of the structural vulnerability to inform more reliable risk assessments for the current building stock and for the improved construction methods proposed in the guidelines. This ultimately provides an avenue to establish proper disaster preparedness strategies by stakeholders, e.g., government and non-governmental organisations.

The experimental study presented in this paper is an intermediate stage in the process of developing a risk assessment framework for East African countries, based on enhanced local data for hazard, exposure and vulnerability (Goda et al., 2018). This work aims to quantify the material properties of local masonry construction in Malawi. It provides useful data for the development of structural vulnerability evaluation tools for masonry structures in Malawi.

2 METHODOLOGY

2.1 *Preparation of materials and specimens*

An extensive experimental programme was designed and implemented at the Civil Engineering Laboratory, University of Malawi-The Polytechnic. The experiments were set up based on building surveys and in-situ test results of material strengths, which were investigated in the previous stages of this work (Goda et al., 2018; Novelli et al., 2019).

The vast majority of the housing construction is based on low-quality, locally moulded and fired bricks, with compressive strengths between 1 and 10 MPa (typically lower than 5 MPa). These bricks are bonded with mud or sand-cement mortar mixtures, the cement-to-sand ratio of which signficantly deviates from the recommended values of 1:4 for structural masonry (1:3 for foundations and special applications) according to MS791-1 (Malawi Bureau of Standards, 2014) and the minimum limit of 1:6 recommended in the Safer House Construction Guidelines (Bureau TNM, 2016). In local construction practice, the cement to sand ratio depends on the income level of the household and it is generally lower than 1:6, often 1:8 or even lower.

The second important aspect is the effect of the local construction conditions on the quality of the final masonry construction. Housing construction in Malawi takes place exclusively during the dry season hence curing conditions are naturally unfavourable. This, combined with high water absorption of local clay bricks and low-quality surfaces (i.e. dusty surfaces with loose particles), results in weak bonding conditions. In an experimental programme, these effects should be considered to obtain realistic values.

Due to these considerations, the testing programme followed established methods and standards, with exception of the specimen preparation and curing, which were specially designed to replicate the actual field conditions. Firstly, bricks used for the construction of specimens were sourced from ordinary commercial local production batches that exhibited the same range of strength values and variability as in the field. Nominal brick dimensions were 200mm × 90mm × 50mm, exhibiting some deviation. Secondly, four different mortar materials were used: three cement-to-sand mix ratios of 1:4, 1:6, and 1:8, plus mud mortar (M). For the cement mortars two different conditions were considered: a) "Unfavourable" with mortar applied on dry and dusty bricks and b) "Favourable" with bricks soaked in water prior to masonry construction. Hereafter, a letter "F" or "U" is added to the mortar type to indicate the simulated bonding conditions, e.g., 1:4F implying favourable and 1:4U unfavourable.

2.2 *Testing programme*

The testing programme included tests on material properties and tests on the behaviour of the masonry composite, which are described in national and international specifications. More specifically:

a) Tests on materials: uniaxial compression and 3-point bending. These were to characterise the mechanical properties of bricks and mortar samples. Mortar cubes with dimensions of 50mm x 50mm x 50mm were used for compression, and mortar prisms with dimensions of 160mm × 40mm × 40mm were used for flexure, according to (MS6, 1994, MS777, 1997, EN 1015-11, 1999).
b) Tests on interfaces: direct tension on crossed brick couplets (ASTM C952) and interface shear on brick triplets (EN 1052-3, 2002). These were to obtain the tensile and shear resistance of the interfaces. Three different levels of lateral confinement pressure were applied to allow the calculation of Mohr-Coulomb shear failure criterion parameters (i.e. cohesion and friction angle).
c) Tests on prisms and panels: compression of masonry prisms of five bricks high to satisfy standard slenderness limits (EN 1052-1, 2002), diagonal shear of square panel of five brick units long (around 1060mm), implementing an in-situ variant of the standard method presented by Brignola et al. (2008), and out-of-plane flexure of panels in two different axes, parallel and perpendicular to the brick bedding joints (EN 1052-2, 2002, MS791-1, 2014). In both cases, the span of the supports for the bending specimens was 800mm, to satisfy standard length to thickness limits (MS791-1, 2014).

For most of the tests, at least 6 specimens were prepared for each of the different test configurations described above. In the case of the triplet interface shear strength, only 3 specimens per confinement level were tested (12 overall for each configuration), due to the large number of tests. For the last two tests on the large panels, only two combinations were considered: 1:4F, to simulate a “strong” configuration and 1:6U, for a “weak” configuration, respectively.

The testing equipment consisted of a combination of conventional laboratory testing devices with some portable testing rigs mountable on the specimens directly and on the laboratory’s strong floor, and a high-precision video tracking system for measurement of displacements (Imetrum Video Gauge), with synchronised analogue load cell signals connected onto it. Some typical photos of the basic testing configurations are shown in Figure 1.

Figure 1. Typical testing configurations

3 RESULTS AND DISCUSSION

3.1 *Test results for bricks and mortars*

Despite being from the same batch, the brick samples tested for compressive strength, corresponding to 1% of the total batch exhibited variable strength as shown in Figure 2.

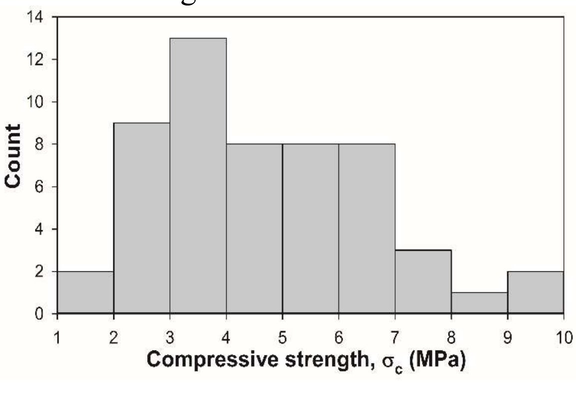

Figure 2. Distribution of compressive strength of bricks.

The range of the measured strengths in the laboratory is consistent with values obtained from in-situ field testing of material strengths from various areas and local production sites in Southern and Central Malawi.

The results of compressive and flexural strengths of mortar are presented in Figure 3 and Table 1, respectively. Two sets of samples from the same mortar production were tested, the first one was cured by water immersion for 28 days and the second one was air-dried without water immersion. From the measured values shown in the graph and the table, the reduction of strength with decreasing cement content in the mixture and high reduction of strength (60%) due to bad curing conditions, are obvious. Moreover, the weakest cement mortars under bad curing conditions, proved to be as weak as the traditional mud mortar material.

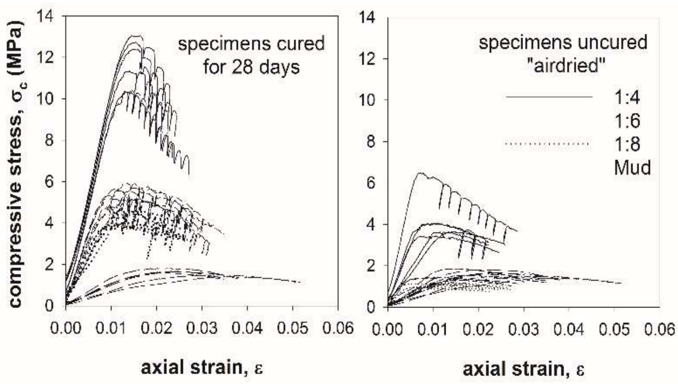

Figure 3. Compressive strength of mortar materials

Table 1. Flexural strength of mortars (MPa)

Mortar material	Cured in water		Air-dried	
	Mean	COV	Mean	COV
1:4	2.45	0.08	0.79	0.39
1:6	0.66	0.43	0.20	0.46
1:8	0.39	0.50	0.16	0.40
Mud	-	-	0.23	0.49

*COV is coefficient of variation.

3.2 *Masonry prisms in compression*

Results for compression test of masonry elements are shown in Figure 4 for the strongest and weakest combinations. It is known from the literature that the strength of the masonry composite is normally lower than the strength of the brick units, which are considered to be the strongest component, due to the lower strength and higher compressibility of the mortar (Kaushik et al., 2007). However, in this case study, the strength of the bricks is comparable and is in some cases even lower than the mortar strength. As a result, the compressive strength of all prisms falls within a narrow range. The failure mechanism was found to be characterised by local crushing of the weakest brick in the stack, according to the distribution shown in Figure 2. Typical photos of uniformly distributed and local crushing mechanisms are shown in Figure 5. The measured values are much lower than the values from the literature. On the other hand, values around 1MPa could be sufficient to carry low vertical loads for light-weight roofs of low-rise Malawian structures (Novelli et al., 2018). For example, a minimum strength of 1.2MPa is required for earthquake resistant adobe masonry according to IAEE (2004). In this sense, structural details, such as wall thickness, are more critical for structural integrity than the compressive strength alone.

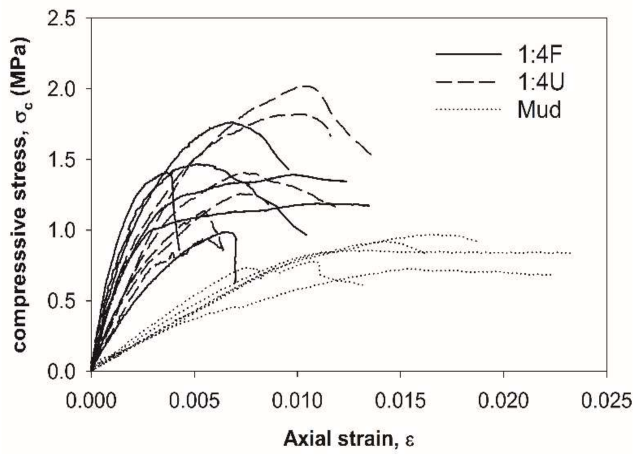

Figure 4. Compressive strength of brick prisms.

Figure 5. Failure modes of masonry prisms in compression; note the local brick crushing mechanism in the bottom pictures.

3.3 *Tensile strength of interfaces*

Results from the crossed couplet tension tests are summarised in Table 2. The maximum tensile resistance for the strongest 1:4 and 1:6 configurations was not possible to be measured due to the failure of weak bricks before failure of the interfaces (Figure 6). Thus, a better method, such as the bond wrench (ASTM C1072, 2013; EN 1052-5, 2002) could be more applicable compared to the crossed couplet test. From these results, it is obvious that the mud mortar material performed much worse than the cement mortars in terms of interface adhesion. Practically, increasing cement ratios improves the interface adhesion, even though the results had significant scatter and were quite sensitive to the specimen's surface condition and workmanship.

Table 2. Tensile strength of interfaces (MPa)

Mortar material	Favourable (F)		Unfavourable (U)	
	Mean	COV	Mean	COV
1:4*	0.092	0.26	0.049	0.53
1:6*	0.053	0.37	0.049	0.23
1:8	0.039	0.32	0.040	0.78
Mud**	0.008	0.48	-	-

* It was not possible to measure the maximum values, because many bricks failed before the interface
** F and U conditions were considered only for cement mortar materials

Figure 6. Crossed couplet method and associated problems due to very low strength bricks

3.4 *Shear strength of interfaces*

Results for the shear resistance of interfaces are shown in Figure7.

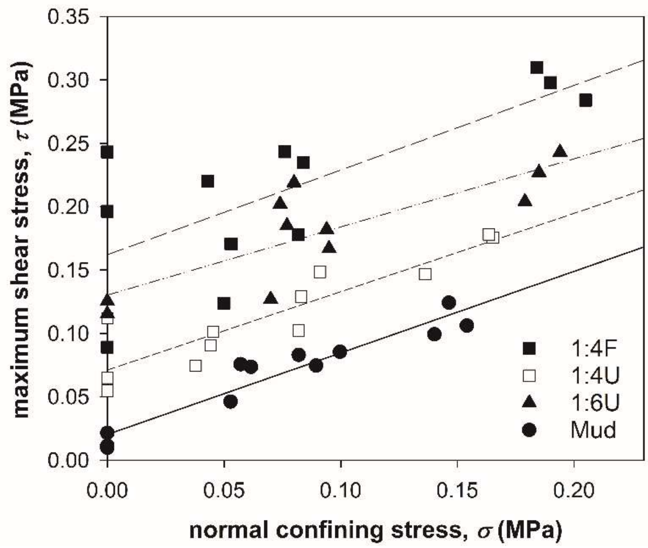

Figure 7. Variation of shear strength of interfaces with increasing confinement

As expected, the quantity of cement and the bonding conditions affect the strength of the interfaces. Measured values for interface cohesion range between 0.02 MPa for mud mortar and 0.2-0.25 MPa for the strongest cement mortar configurations. Friction angles were measured at around 32 degrees.

3.5 *Panels in diagonal compression shear*

The results for the panel shear testing are shown in Figure 8, based on the more accurate RILEM method, over the simplified ASTM approach (Brignola et al., 2008). The results are consistent with the interface resistance measured from the triplet shear tests. The differences in strength and stiffness are obvious for the different configurations. Adobe masonry is around five times weaker compared to the weak 1:6U specimens, which is around three times weaker than the stronger 1:4F. From the stress-strain curves, premature failure of many specimens can be observed, corresponding to parallel sliding along a "weak" joint, rather than a diagonal crack (see typical failure modes in Figure 9).

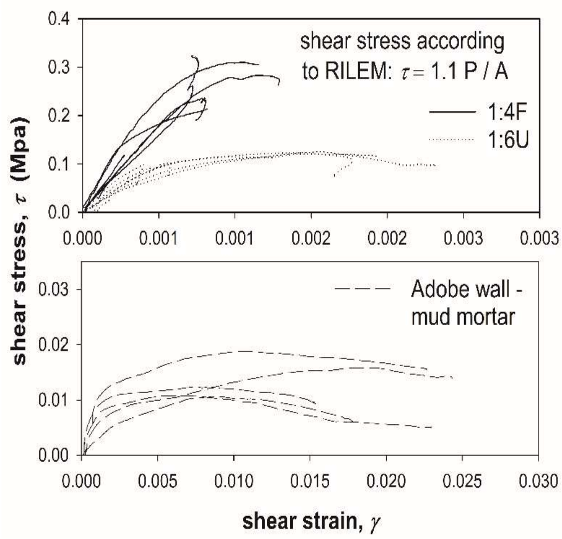

Figure 8. Shear stress-strain curves for wall panels

Figure 9. Typical failure modes in diagonal shears tests; note the bed joint failure mechanism and the associated "dry" joint

The results for both strength and stiffness are considerably lower than the ones from the literature. This is attributed to the relative sliding at the interfaces due to low bonding strength.

3.6 *Panels in flexure*

The behaviour in out-of-plane flexure is the most critical parameter for the performance of masonry structures during seismic loading. From the results shown in Table 3, it is interesting to note that the quality of the interface bonding governs the behaviour. First, in the case of flexure parallel to the brick bedding joints, where the flexural tensile stress is applied exclusively on the horizontal brick-mortar interfaces, no significant difference was shown between the 1:4F and 1:6U configurations. This was because there was a weak "dry" joint within the stack, which failed first. As a result, rarely the crack was observed in the middle span of the bending beam, i.e. the location of maximum deflection. In the case of flexure perpendicular to the brick courses, there was a notable difference in the strength and failure mode. The weaker 1:6U panels failed due to parallel sliding of the bricks on the interfaces, with the bricks left intact, whereas the stronger 1:4F failed with a vertical crack passing through vertical mortar joints and bricks. Some photographic evidence of these different failure modes observed is provided in Figure10.

Table 3. Flexural strength of panels (MPa)

Brick bending	1:4 F		1:6 U	
	Mean	COV	Mean	COV
Parallel	0.045	0.39	0.05	0.41
Perpendicular	0.54	0.24	0.33	0.35

*COV is coefficient of variation

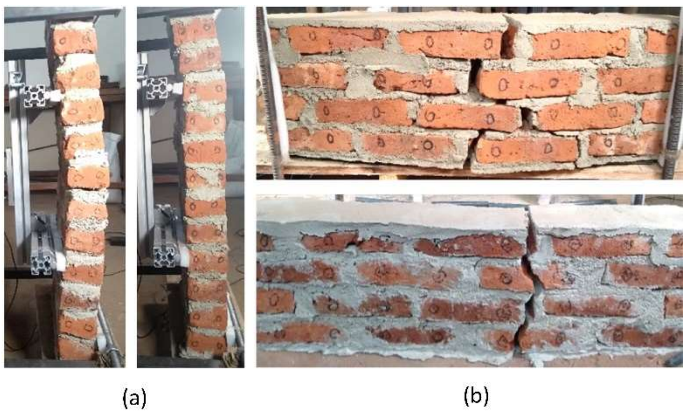

Figure 10. Out-of-plane flexural failure modes: (a) parallel and (b) perpendicular to the brick bending

4 CONCLUSIONS

A brief overview of the experimental results, which are indicative of the strength of Malawi masonry construction, has been presented. These results will inform structural fragility models for the purpose of developing a realistic earthquake risk assessment tool, based on enhanced local data. The main conclusions of this study can be summarised as:

1) Significant variation of material properties and local construction conditions leads to a large scatter of strength results for low-quality masonry in Malawi. The values to be used in fragility modelling should reflect this large variability in material strengths in a probabilistic manner. Despite the scatter of the results, characteristic trends of the structural behaviour for the various configurations were able to be observed.
2) The compressive strengths of local fired bricks and mortars were much lower than typical literature values. The behaviour of the masonry prisms was found to be governed by the low strength brick units, and was generally lower than 2MPa.Given the low gravitational loads, low strength values in the range of 1MPa can be sufficient for earthquake resistant masonry, provided that other critical structural design parameters, such as the wall thickness, are respected. In other words, low compressive strength is not solely responsible for high vulnerability of Malawian structures.
3) The main vulnerability features of Malawian masonry, with respect to horizontal seismic action are the low in-plane shear and out-of-plane flexure resistance. These are directly related to the quality of the brick-mortar interface bonding and the thickness of the walls. Low cement-to-sand ratios for the mortars and bricks with high water absorption and dusty surfaces due to material loss result in unfavourable bonding conditions. In addition, common local construction practice in Malawi, based on single-skin walls (Novelli et al., 2018), contrary to the recommendation of national and international guidelines (IAEE, 2004; Bureau TNM, 2016), leads to weak out-of-plane behaviour.

5 ACKNOWLEDGEMENT

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6 DATA AVAILABILITY STATEMENT

This publication is in compliance with EPSRC Open Access framework. All underlying data are available to download from (Kloukinas et al., 2019).

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